Editor's Comment's, continued from page 2.
the status of the NEWSLETTER in this issue). This is the possibility for members to offer items for sale or seek items wanted as part of the "Used and Out-of-Print Books and Related Items" column. Such items should be related to the profession, and the other restrictions mentioned in the status report will apply. Send a letter to me if you have such an item, or an opinion about the idea.

August is the prelude for the start of a new school year, the start of a new US federal budget year, and a return to work after vacation for many. I hope this time finds all members prosperous and well.

President's Message, continued from page 3.
Propagation. He noted that the special issues planned during 1986 would require an increase in the number of pages to be printed. He also expressed concern about the percentage of authors who were paying page charges. In 1984, this percentage was lower than anticipated and continuation of this trend could have serious ramifications for the Society's finances. AdCom asked that the Publications Committee consider this matter and other long range questions relating to the Society's publication. The publication committee was also asked to begin looking for a replacement for Ron, who will be completing his term as Editor next year. If you have any suggestions on Ron's successor, please contact Walter Kahn with your input. Ron Fante is doing an outstanding job as Editor, and his replacement will have a tough act to follow!

The AdCom considered other matters related to the technical services offered by our Society to the membership. For example, the percentage of papers accepted by symposia technical committees was discussed briefly. It was decided that this topic should be considered carefully by the Long Range Planning Committee, which is chaired by Bob Mailloux. Bob's committee was also changed with the task of developing long range policy with regard to workshops that are sponsored by the AP-S. Most of us are familiar with the successful AMTA workshops that were run in conjunction with the Boston and Vancouver meetings. AdCom feels that workshops such as these might be expanded in the future. To get the ball rolling, I asked Bill Scott to organize an AdHoc committee that will look into the matter of future workshops. These workshops need not take place concurrently with AP-S symposia but could be sponsored by local chapters in the future. Their duration might also vary depending on the material to be covered. In any case, we look forward to having Bill's committee propose some interesting alternatives during the coming year.

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The AP-S Newsletter publishes paid advertisements on short courses, job opportunities, etc., which are of interest to the AP-S membership. The price schedule for ads in the Newsletter is:

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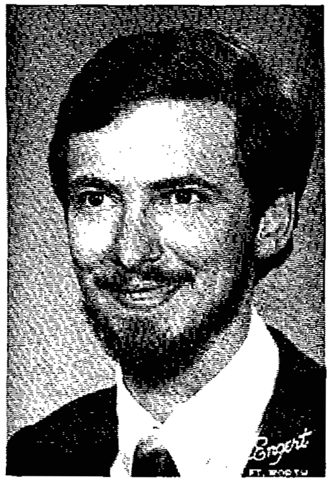
Introducing David Rutledge Feature Article Author



David Rutledge was born in Savannah, Georgia, on January 12, 1952. He received the BA degree in mathematics from Williams College, Williamstown, Massachusetts, in 1973, the MA degree in electrical sciences from Cambridge University, Cambridge, England, 1975, and the PhD degree in electrical engineering from the University of California at Berkeley in 1980. From 1975 to 1976, he was at the General Dynamics Corporation in Fort Worth, Texas, working on a microwave data link for the F-16 aircraft.

In 1980 he joined the faculty at the California Institute of Technology, Pasadena, California, where he is now associate professor of electrical engineering. He received the IBM faculty development award in 1983 and the NSF Presidential Young Investigator Award in 1984. His research is in developing millimeter and submillimeter-wave integrated circuits and applications.

Feature Articles Solicited for Newsletter

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The editorial Staff of the AP-S *Newsletter* continues to actively solicit feature articles which describe engineering activities taking place in industry, government, and universities. Emphasis is being placed on providing the reader with a general understanding of the technical problems being addressed by various engineering organizations as well as their capabilities to cope with these problems. If you or anyone else in your organization is interested in submitting an article, we encourage you to contact Editor Ross Stone to discuss the appropriateness of the topic. He may be reached at the above address.

Feature Article

Substrate-Lens Coupled Antennas for Millimeter and Submillimeter Waves

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Antennas at millimeter and submillimeter wavelengths present formidable challenges. One approach is to scale up lower-frequency microwave systems of hollow-metal waveguides and horns. The problem with this is that as the frequency goes up, the waveguides get smaller, and the fabrication becomes difficult and expensive. Another way is to follow the lead of low-frequency integrated circuits and develop monolithic integrated circuits. This is attractive because there is the possibility of integrating thin-film metal antennas, solid-state devices, and low-frequency processing circuits, all on the same chip. Moreover, a large number of devices can be made together simultaneously to form an array or imaging system. This means we should develop antennas that work on the common integrated-circuit substrates: quartz, silicon, and gallium arsenide.

Antennas on substrates

It is characteristic that an antenna on a dielectric substrate radiates most of its power into the substrate rather than into the air [1]. Fig. 1 shows a slot and a dipole on a substrate. Fig. 2 shows the theoretical patterns for these antennas when they are much shorter than a wavelength. The power in the air for both is much smaller than the power in the dielectric. Notice also that the patterns are not complementary. Babinet's principle does not apply when the dielectric is not homogeneous.

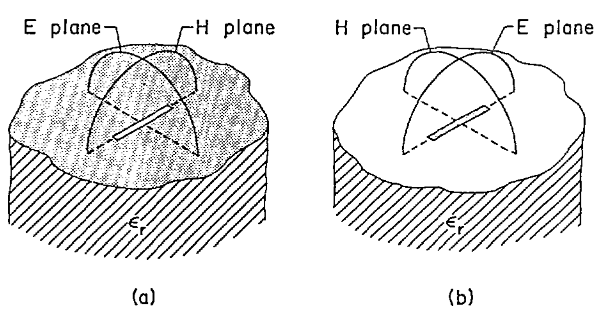

Fig. 1 Slots (a) and dipoles (b) on a dielectric substrate.

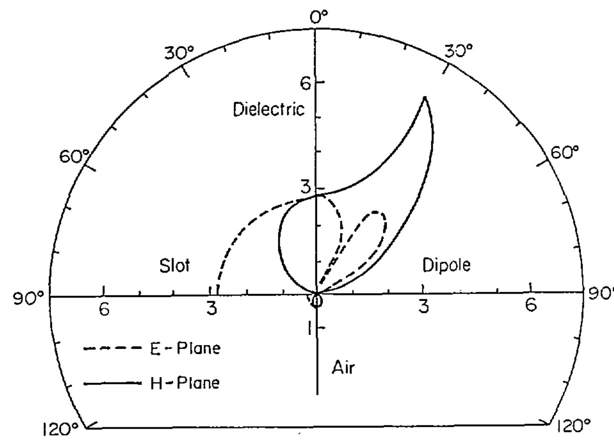

Fig. 2 Contrasting patterns of an infinitesimal slot (left), and a dipole (right), on a substrate. The power radiated up is power into the substrate. The substrate dielectric constant is 4, appropriate for fused quartz.

The ratio of the two powers is $\varepsilon_r^{3/2}$, where ε_r is the dielectric constant. Quartz is an insulator with a dielectric constant of 4, and silicon and gallium arsenide are semiconductors with high dielectric constants between 12 and 13. This means that we expect only 13% of the power to go into the air above quartz, and 2% above silicon or gallium arsenide.

It is easy to understand why a slot radiates more power into the substrate, because the power radiated by an infinitesimal slot in a homogeneous dielectric is proportional to $\varepsilon_r^{3/2}$. For a dipole the physics is more subtle. It can be understood by considering a receiving dipole, which produces a voltage that is proportional to the local electric field. At an interface, the local electric field is the sum of two fields, the incident field and the reflected one. Everything depends on whether the reflected field is in phase or out of phase with the incident field. When the wave is incident from the air, the reflected field is 180° out of phase with the incident field, and they tend to cancel each other. The resulting field is small, and so is the dipole signal. When the wave is incident from the dielectric the reflection is in phase with the incident field, and this adds to the field that the dipole sees. This means that the dipole response is large for radiation incident from the dielectric side.

If one wants to couple energy into an antenna on a dielectric, one should come from the substrate side. Some early investigators did appreciate this fact, and when they made dipole antennas on substrates to receive submillimeter and infrared radiation, and they were puzzled by the low coupling efficiencies (1-3%) that they measured for radiation coming from the air side. They should have turned the substrate over and come through the back side.

But turning the substrate over does not completely solve the problem. Substrate modes are also important. This is easier to understand in a transmitting antenna (Fig. 3). The rays that are transmitted at angles larger than the critical angle are completely reflected and trapped as substrate modes. This power can be up to 90% of the total power. By reciprocity, a receiving antenna suffers the same loss.

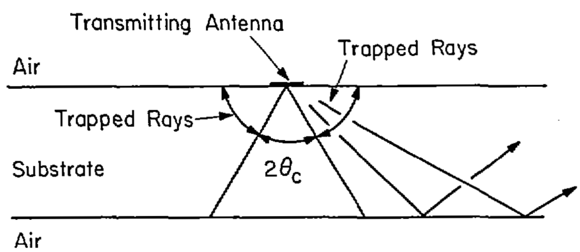

Fig. 3 Transmitting antenna on a substrate, showing the rays trapped as substrate modes. The critical angle is 30°, appropriate for fused quartz.

Substrate-lens coupled antennas

Several investigators have worked on solutions to these problems. Professor Nick Alexopoulos' group at UCLA has investigated choosing the layers and thicknesses carefully to enhance the radiation and reduce substrate-mode losses, while Professor Sigfrid Yngvesson's group at the University of Massachusetts is developing Vivaldi antennas that effectively harness the substrate mode as a surface-wave antenna. Our approach has been to put a lens on the back side of the substrate, and focus the incident radiation through the lens (Fig. 4). This takes advantage of the fact that the antenna responds primarily to radiation from the substrate side. It eliminates the substrate modes, because the transmitted rays are now incident nearly normally on the lens surface.

The disadvantages of the substrate lens are the same as for any system with refractive optics: reflection loss and dielectric loss. The reflection loss is particularly important for a silicon lens, because of the high dielectric constant. However, it has proved

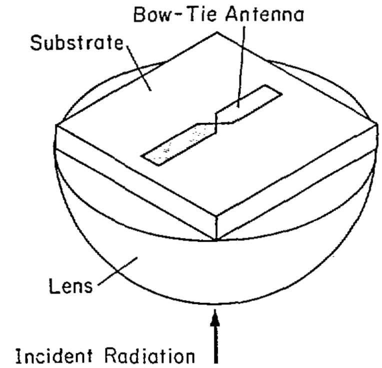

Fig. 4 Substrate-lens coupled antenna.

possible to eliminate this loss almost entirely with a polystyrene cap that acts as a matching layer [2]. Afsar and Button have made also excellent measurements of the dielectric losses [3].

Imaging arrays

The major application of substrate-lens coupled antennas so far has been in imaging arrays (Fig. 5). An image of an object is focused through an objective lens and a substrate lens onto an array of antennas and detectors. The signal detected at each antenna is plotted to form the image. The antennas are spaced at an interval that satisfies the Nyquist sampling criterion (typically two antennas per dielectric wavelength), so that the signals can be interpolated to recover the original image. The advantage of an imaging array is that it can make mechanical scanning unnecessary. This is important where the object is changing quickly, or more integration time is needed to improve the signal-to-noise ratio.

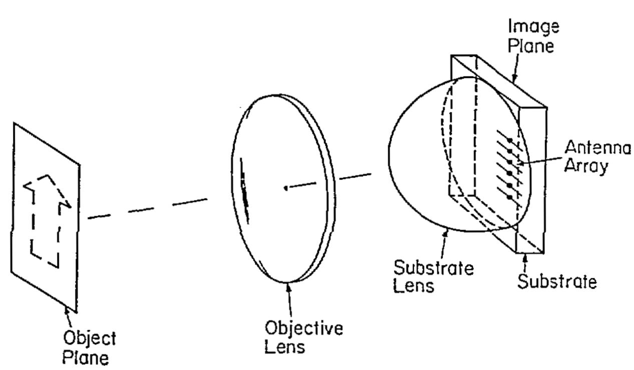

Fig. 5 Imaging antenna array.

Fusion-plasma diagnostics

Fig. 6 is a microscope photograph of a 300-GHz imaging array for plasma diagnostics. The antenna is a modified bow-tie with a bismuth microbolometer detector at the apex of the bow. This antenna is non-resonant, with patterns that resemble the dipole patterns in Fig. 2. In an imaging array, each bow tie acts as a feed antenna for the objective lens. The typical feed efficiencies for single bow ties are between 25% and 35%. One of the interesting features of the bow tie on a dielectric is that its leads can be extended to form the low-frequency connections. No RF isolation filter is necessary.

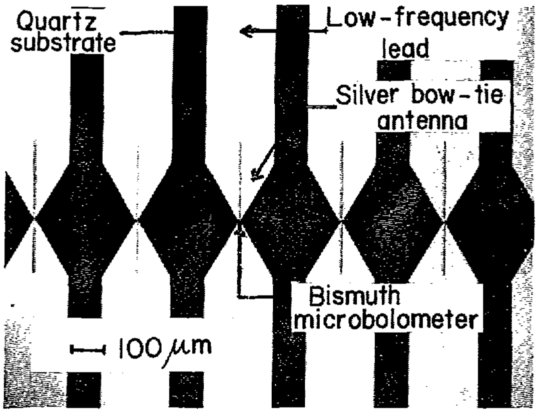

Fig. 6 300-GHz microbolometer array. The dark background is the quartz substrate, and the light areas are the silver bow-tie antennas. The narrow strips are bismuth, and form microbolometer detectors where they cross between the antenna leads at the apex of the bow. This array was made by Dean Neikirk, then a graduate student at Caltech, and now at the University of Texas.

Peter Young, then a graduate student in Professor Neville Luhmann's group at UCLA, and now at the Princeton Plasma Physics Laboratory, used this array to make an image of the electron density in a tokamak plasma (Fig. 7) [4]. The idea is that the electrons in the plasma affect the refractive index,

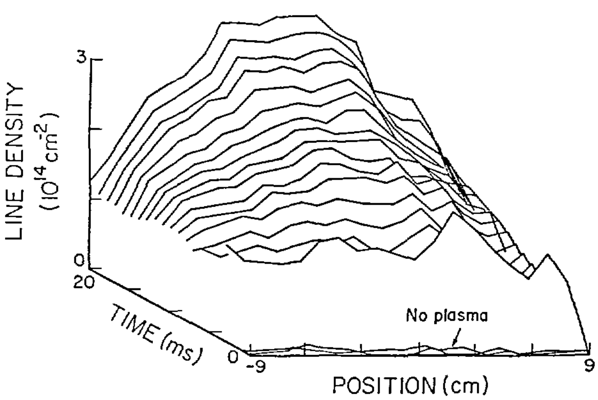

Fig. 7 Holographic phase image of the electron density in the UCLA Microtor tokamak, measured with a twenty-antenna microbolometer array. The x axis is the position across the vacuum chamber. The plasma density is building up at the start of the shot (from [4]).

and that this change can be calculated by measuring the phase shift of the beam through the plasma.

Schottky-diode arrays

The bismuth microbolometers are very useful at submillimeter wavelengths, but they are slower and less sensitive at millimeter wavelengths than Schottky diodes. Chung-en Zah, then a graduate student at Caltech and now at the Bell Communications Research Laboratories, succeeded in making a monolithic Schottky diode array with nine diodes (Figs. 8 and 9) [5]. The diode array is on a gallium-arsenide substrate. The substrate lens is made of silicon, with a polystyrene cap. He measured a double-sideband conversion loss of 11.2dB. For

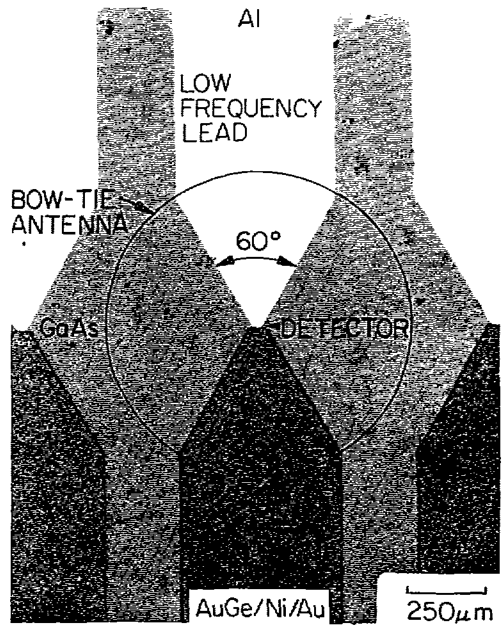

Fig. 8 90-GHz Schottky-diode imaging array (from [5]).

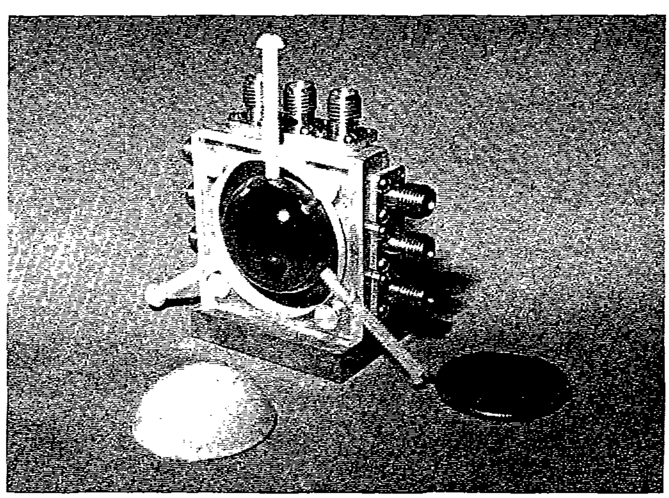

Fig. 9 Assembled 90-GHz Schottky-diode imaging array, showing the polystyrene cap that acts as a matching layer (from [5]).

comparison with waveguide systems, 4.7dB of the loss is attributed to the coupling efficiency of the antenna, 1.5dB to losses in the lenses, and 5dB to the diode itself.

Radio-astronomy receivers

There has been an exciting new development in lens-coupled antennas in radio astronomy. Mike Wengler, a graduate student in Thomas Phillips' group at Caltech, has built a single bow-tie antenna on a quartz-substrate, with a quartz substrate lens [6]. The detector is a superconducting tunneling device called an SIS junction (superconductor-insulator-superconductor). The devices operate at the temperature of liquid-helium, 4.2K. The cooling also reduces the absorption loss in the substrate lens. Wengler's device has demonstrated excellent sensitivity and an enormous bandwidth, **from 100GHz to 500GHz.** The measured double-sideband conversion loss varies from 7dB at 100GHz to 12dB at 500GHz, and the double sideband mixer noise temperature varies from 100K at 100GHz to 500K at 500GHz.

Future work

There is much work to be done. Accurate measurements and theory for the bow-tie patterns are not available. Also, one would like to improve the feed efficiency of the bow ties. Preliminary work has shown that other antennas should have better feed efficiencies. Peter Tong, then a graduate student at Caltech, and now at the Hewlett-Packard Company, found that logarithmic spiral antennas on substrates have better patterns than bow ties. Peter Siegel, at the National Radio Astronomy Observatory, has also found improved patterns for a log-periodic antenna on a substrate. Preliminary work by Richard Compton, a graduate student at Caltech, indicates that a two-dimensional array of diamonds should have a feed efficiency near 90%.

Another interesting question is, how small can the substrate lens be made? One of the interesting features of Wengler's work is that the radius of his substrate lens was less than two free-space wavelengths at 100GHz. Using a smaller lens would reduce the absorption loss, and would make it more attractive at the lower millimeter-wave frequencies.

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